STUDIES FOR STUDENTS.

EROSION, TRANSPORTATION, AND SEDIMENTATION PERFORMED BY THE ATMOSPHERE.

IN dynamical geology there is one line of inquiry which has received, comparatively speaking, but little attention from American geologists. Our text-books discuss in a thorough manner the work performed by water, and they also tell us much about the work of earthquakes, of volcanoes, and of glaciers. Some of these phenomena appear so striking as always to challenge our attention. Others are so common in their occurrence and so obvious that they suggest themselves to our study and to our reflection everywhere. The work performed by the winds in the atmosphere appears hardly to have received its due share of attention. The transportation of solid materials by the air is one of those subtle operations in nature, which are apt to escape our observation. The process is of an unobstrusive nature, and only in certain localities becomes at all obvious. There are, however, some scientists who have understood and urged the great importance and efficacy of aerial transportation in geological dynamics. Ehrenberg, Von Richthofen and Pumpelly will be remembered first in this connection. Blake, Gilbert, Hayden, N. H. Winchell, Chamberlin, Merrill, and others have described instances of erosion and transportation by the atmosphere. But it will be conceded, I think, that the subject has not received any general and searching attention from geological students in this country. This is the only excuse for presenting at this time a few considerations bearing on the topic. I take the liberty to state in a dogmatic way what appear to me to be some laws governing aerial erosion, transportation and sedimentation in general. It is not claimed that these statements contain much that is new in substance.

As an agent of erosion air is far less efficient than water.

The chief circumstance on which this inefficiency depends is the small weight of the air, which is only about $\frac{1}{813}$ as heavy as water. Moving with the same velocity it will strike with a force only $\frac{1}{813}$ as great as that with which water will strike. The effectiveness of the impact, however, or the striking force, increases as the square of the velocity and thus when the velocity of the wind is 28 (—813=28) times greater than that of a current of water, the impinging force of the two currents is the same. Velocities 28 times greater than those of many rivers are not uncommon in the air a small distance above the ground. But the lightness of the air enables even a scanty vegetation to greatly slacken the speed in the currents immediately in contact with the ground. This slackening of the impinging current is apparently sufficient to effectually protect even loose soil from wind erosion under ordinary circumstances. Such is at least the case where the soil is moist and where the land is level.

As an erosive agent, the atmosphere is at a disadvantage also in another respect. Lakes never erode their bottoms below the plane of wave action, and even in rivers erosion is greatest at the shores where this plane meets the land surface. Were it not for the wave action, the erosion by continental waters, as well as by the waters of the oceans, would be greatly reduced in its efficacy. In fact we generally look at that part of the surface of the earth which is under water, as being an area of deposition and sedimentation, and at the land above water and the coast lines alone, as being areas of erosion. Whatever be the height of the atmosphere, it does not appear likely that its upper limit is a well defined plane with waves as on the sea. But even if it be, this wave plane would be high above the most elevated point on the earth's surface. There is, therefore, no plane of wave-erosion in the atmospheric sea. Such work of this kind as is performed by the air can only be compared with that which takes place in the ocean far below its plane of wave-action, and rather in its abysmal region. Evidently this is not very great, if of any consequence at all.

Wind erosion becomes geologically important only in certain localities, and the conditions favoring it are a dry climate and a topography of abrupt and broken reliefs.

On plains where the ground is dry and vegetation scanty or absent, ordinary strong winds are apt to slowly wear into the soil, where the roots of plants do not protect it. If such soil contains sand which is too coarse to be lifted up and carried away, dunes are formed, and the uneven topography thus developed still more favors wind erosion; for it is evident that the slopes of the dunes will be struck with greater force than the even surface of a level plain. In such places the sand grains are triturated and worn, and the abraded material is promptly removed. It is also evident that where a country is traversed by vertical escarpments and cliffs, and steep slopes, strong eddies are set up as the wind strikes these reliefs. Where the rocks are of fine materials and but little indurated, like most of the Mesozoic and Cenozoic beds of the west, it would be singular if such eddies did not erode the bare surfaces of their outcrops. It does not appear practicable to estimate separately the erosion produced by impact of the air alone, and the abrasion produced by the materials carried. The ratio between the two will, of course, vary with the quantity of the load. Where this is considerable, abrasion is no doubt proportionally greater than in water, for the speed of the impinging particles is here much higher, and their striking force consequently greater. Occasionally this circumstance greatly intensifies aerial erosion and produces a natural sand-blast, which is very effective in its action on solid rock. That such abrasion becomes appreciable and important along the escarpments of "mesas" in dry regions appears not to admit of a doubt. In such places the driven sand may sometimes be felt smiting the exposed skin of the traveler.

The speed of the wind being lowest near the surface of the ground, materials must by some means be lifted through this zone of low velocity in order to be transported any considerable distance by the atmosphere.

According to some observations made by Stevenson, the aver-

age velocity of the wind increases very fast and apparently not according to any definite law upwards for the first fifteen feet above the ground. Above this height it increases as the bisected chords of parabolas having their vertices in a horizontal line 72 feet below the surface. The parameters of these parabolas increase directly in the ratio of the squares of the velocities of the different winds. With a velocity of ten miles per hour at an elevation of fifty feet above the ground there will then be a velocity of about one hundred miles per hour one mile above the ground, but of less than one mile per hour near the surface. Observations made on the movements of clouds verify these calculations as to high velocities some distance up in the atmosphere. Whatever is to be transported any great distance must be lifted up to some considerable height above the surface of the earth, where the winds attain high velocities.

Over level plains, under ordinary circumstances, the conditions seem to be unfavorable for effecting any such upward transference, and little or no removal of material is apt to take place. But when a strong wind runs up against a vertical cliff, such as are seen in the bad lands or in the country of the plateaus and "mesas," eddies are no doubt set up which rise high above these vertical reliefs. A short valley or a reëntrant excavation in such a cliff will gather the wind and start it with increased force obliquely upwards, as it enters from the open end. In such a mobile element as the atmosphere an eddy like this may rise a considerable distance. No less effective in this respect are the whirlwinds in arid regions, which have been described by nearly every traveler in such countries.[1] During the warm part of the day these can be seen, it is said, at almost any time in some direction of the horizon. They often rise to a great height, carrying with them the loose materials of the desiccated soil and giving them up to the incessant and steady run of the winds above.

The explosive outburst of a volcano similarly launches enormous quantities of minute fragments of pumice on the currents

[1] GEO. P. MERRILL, Engineering Magazine, Vol. II., p. 599 *et seq.*

of the atmospheric ocean, throwing them upwards sometimes over 10,000 feet. Small quantities of incombustible matter are raised to the horizon of translation above by heated currents of air from chimneys and fires, and perhaps still smaller quantities by birds and other animals of flight.

Aside from these instances there are no important means by which the atmosphere is loaded, and for this reason, among others, its importance as a geological agent is small. The load to be carried must be raised before it is borne away. In water the contrary is almost always the case. The material to be transported is supplied at the water's surface and from the start to the end of the transport the sediments are allowed to slowly sink. They are transported forward and downward; in the atmosphere they must be transported first upward, and then forward.

To be subject to transportation by the atmosphere, rock materials must be finely comminuted, the average largest size of quartz particles that can be sustained in the air by ordinary strong winds being about .1 mm. in diameter.

This statement is based on a number of measurements, which have been made on sand and dust transported by the air. Among these are measurements of dust and sand raised by the wind from roads and streets in dry weather; of dust which fell on the ground at Kansas City, Mo., after a severe west wind on the plains; of dust collected after dry storms on the window-sills in residences in the central part of Kansas; of sand taken in crevices and corners in railroad cars in various parts of the country. It agrees with measurements made on volcanic dust known to have been carried several hundred miles in the atmosphere. Corroborating results have also been obtained by some simple experiments. The constituent materials of a coarse loam were separated into groups of different grades of fineness. These separations were thrown into the air and observations made on their behavior. The velocity of the wind was about eight miles per hour, and the observations may be tabulated as follows:

Average diameter of particles.	*Behavior of the particles when thrown into the air.*
.75 mm.	Described a path diverging about 10° from a vertical line.
.37 mm.	Described a path diverging about 45° from a vertical line.
.18 mm.	Described a path diverging but a few degrees from a horizontal line, were blown upward by eddies.
.08 mm.	Could scarcely be noticed to settle in transport.
.04 mm.	Apparently completely borne up by the wind.
.007 mm.	Completely borne up by the wind.
.001 mm.	Completely borne up by the wind.

It is hardly necessary to add that the average size of the largest particles carried varies greatly with the velocity of the wind. Sand grains will occasionally be found to have been thus carried, which have a diameter many times larger than the average maximum here stated. The presence of such large grains can readily be accounted for by the chances for becoming entangled in specifically lighter objects, such as fragments of leaves and other vegetation, and thus to be carried by them. It will be understood, also, that the statement made above does not apply to that phase of wind-transportation which takes place on the surface of a sand dune, where the sand is as if rolled forwards, nor to that in the very lowest part of the atmosphere generally, where materials are thrown forwards short distances at a time by eddies due to the contact of the atmosphere with the more or less irregular surface of the land.

The capacity of the atmosphere for transporting particles of quartz below the size of .1 mm. in diameter, is very great.

Disregarding the occasional transference of matter by volcanic forces and by living organisms, there are only three principal agents known to be at work removing materials from place to place on the surface of the globe. These are water, ice, and air. It is believed that, with the above limitation as to the fineness of the material, the transporting power of the atmosphere, as compared with that of water and ice, is very great. The transporting capacity of the water in our continental rivers is better known than that of glaciers or of ice fields, and it makes our best

standard of comparison. Let us take, for instance, the work of transportation which is performed by the Mississippi river.

The efficiency of any transporting current is determined by three factors, viz.: (1) the area of its transverse section, (2) the velocity of its motion, and (3) its capacity for holding a load. In the case of the Mississippi basin we may say that the products of disintegration and erosion within its boundaries may be removed by principally two agents, water and air. What is removed by water all passes out through the channel of the lower Mississippi. The size of this current in transverse section is less than $\frac{1}{100}$ of a square mile. It is evident that all the materials removed by this river from its great basin, whether taken from the Rocky mountains or from the Appalachian highlands, must pass through the same narrow circumscribed limits of $\frac{1}{100}$ of a square mile in the lower course of the river. Now, the atmosphere may also be regarded as a current. The width of this current will be the average width of the entire drainage basin of the Mississippi, and in its height this current equals the height of the atmosphere. Taking this to be ten miles, which cannot very well be too much, and taking the average width of the Mississippi basin as one thousand miles—it is at least one hundred miles more—the transverse section of the atmospheric current will be ten thousand square miles. The ratio of the sizes of these two currents as shown in their sections is thus 1 : 1,000,000, *i. e.*, the cross section of the Mississippi current is $\frac{1}{1000000}$ of that of the atmosphere. If velocity and capacity for carrying a load were the same in both currents, the relative transporting power of the greater one would be 1,000,000 times that of the smaller.

In respect to velocity the Mississippi is also less effective in its work than the atmosphere above it. The average velocity of the wind over the interior basin is not less than eight miles per hour, while the average velocity of the lower Mississippi is about .7 mile per hour. The ratio of the velocities is therefore represented by the fraction $\frac{7}{80}$, which is a little less than $\frac{1}{10}$. If, therefore, the two currents were equal as to their cross sec-

tions and as to their capacity for sustaining a load, the current with the greater velocity would be able to remove ten units of sediments, while the slower current would remove one. Multiplying the fraction expressing the ratios between the cross sections of the two currents ($\frac{1}{1000000}$) by the fraction expressing the ratio between their velocities ($\frac{1}{10}$), we obtain a fraction which expresses their relative carrying power, if their capacities for sustaining a load were the same. This fraction is $\frac{1}{10000000}$. If every cubic foot of air in the atmosphere held in suspension as much of sediments as every cubic foot of water in the Mississippi, then the atmosphere would have the power to transport in a given time ten million times the quantity of material transported in the same time by the Mississippi river.

With regard to the capacity for holding solid particles in suspension the air is, however, greatly inferior to water. It is evident that the load which can be carried by the air at ordinary and even in high velocities, is a great deal smaller than that which can be carried by water. The capacity in this respect of any current depends on chiefly three factors: (1) the density of the medium, (2) its velocity, and (3) its viscosity. As to the comparative densities of the two fluids, the air is only $\frac{1}{813}$ times as heavy as water. Another circumstance also comes into consideration. When the particles of a material like quartz are suspended in water, they lose about $\frac{10}{26}$ of their weight in the air, and the force with which they make their way downwards through the water is thus reduced to $\frac{16}{26}$ of what it would be in the air. This still more increases the relative carrying power of water making it 1321 times as great as that of the air ($813(\frac{26}{16}) = 1321$). On account of the greater average velocity of the atmosphere and also by reason of the consequent greater magnitude of its convection currents, this again has the advantage over water. But exactly to what extent these considerations affect the comparison, data are not at hand to determine. It would appear that the advantage connected with these greater convection currents more than outweighs the disadvantage due to the lesser viscosity of air, when compared with water. At such low

velocities and temperatures this difference in viscosity can perhaps be altogether disregarded. The relative power of the atmosphere to sustain a load of fine sediments would, therefore, appear to be no more than, say $\frac{1}{2000}$ of that of river water. But to be certain that this estimate shall not be too high, let us make the fraction $\frac{1}{5}$ of this value and call it $\frac{1}{10000}$. This means that if a cubic foot of water, *e. g.*, in the Mississippi, will hold in suspension 15.48 grams of solid particles[1], then the atmosphere above it can hold in the same manner in a cubic foot $\frac{1}{10000}$ of this quantity, or about .0015 gram. It will be remembered that this is true only for material of a certain coarseness. If it is too coarse, the atmosphere cannot hold it at all; while if it is very fine, considerably more can no doubt be sustained. In order to ascertain approximately the effect of the variation of the size of the particles on the quantity of materials which can be thus suspended in the air, and also to make sure that the above estimate of the total load of sediments which can be sustained is not too high, some simple experiments have been made. These consisted in introducing dust of varied degrees of coarseness into a receiver, and then keeping the air in the receiver in constant agitation at a velocity of about five miles per hour. A certain quantity of dust would in this manner be kept floating in the circulating air, and this quantity was found to vary with the nature of the material introduced. The results may be tabulated as follows:

Average diameter of particles.	*Quantity sustained in one cubic foot of air agitated to an average velocity of 5 mi. per hour.*
.08 mm.	.020 gram.
.04 mm.	.057 "
.007 mm.	.118 "
.001 mm. (and below)	.053 "

This apparently amply justifies the above estimate as to the quantity of dust which can be sustained in a certain bulk of atmospheric air. It is not supposed that the table gives exact determinations for the different materials, for the conditions of

[1] Humphreys and Abbott.

the experiment are of the most delicate kind and a slight change in the velocity will cause a considerable variation in the quantity of the load.

If then the ratio of the sections of the two currents is $\frac{1}{1000000}$, the ratio of their velocities $\frac{1}{10}$, and the ratio of their loads per unit of bulk of the two media is $\frac{10000}{1}$, the ratio of their respective transporting powers is as the products of these fractions, or $\frac{1}{1000}$. This is the same as to say, that if a cubic foot of air can hold in suspension $\frac{1}{10000}$ of the quantity of fine dust held in the same way by the water in the Mississippi river, and if the velocity of the winds in the atmosphere is on the average not less than ten times as great as the rapidity of the current in the river, and if the area of a vertical section of the atmosphere over the valley is 1,000,000 times as large as the area of a cross section of the lower stream,—then the capacity of the atmosphere to transport dust is 1,000 times as great as that of the river.

Atmospheric currents being loaded, mostly, only to the extent of an insignificant fraction of their capacity, their sediments will be better sorted than deposits in water-currents, which are more often loaded to their full capacity.

It is evident that the greater the load carried by any current, the shorter is the average distance from particle to particle while in transport. This increases the chances for the particles to be affected by each others' movements through the medium and thus for coming together to form clusters. This process, which has been called flocculation, causes more rapid sedimentation; for such a cluster of particles will fall faster through the medium than will the separate grains of which it is composed. Flocculation takes place among particles of all sizes, and small particles which would otherwise be retained in the supporting medium, will easily settle when collected into these clusters. Sediments which have been formed under such circumstances will hence contain a proportionally greater quantity of fine material than if flocculation had not taken place. But flocculation increases with the quantity of the load, and since the load of the atmosphere is

at least 1,000 times (under ordinary circumstances perhaps nearer 100,000 times) less per unit of bulk of the carrier than in most waters where sedimentation occurs, it is likely true that flocculation in aerial sediments is not as great as that which takes place in aqueous sediments. Thus the finest materials carried by the air are not deposited in so great a proportion with the coarse material, as they would be if the atmosphere carried a greater load. The finest sediments, say particles below .002 mm. in diameter, settle only during extreme calms, if not first caused to gather in flocculi. This extremely fine material is retained by the atmosphere and must be carried everywhere over the entire surface of the globe, and must also be deposited everywhere, but in such small quantities as not to be noticeable. No small part of it, it may be surmised, is carried from the land and precipitated into the sea. But the coarser sediments, say particles between .002 and .1 mm. in diameter, are less easily retained in the air and therefore occasionally deposited in favorable localities in such quantities as to become an object of geological significance. It is maintained that in these deposits from the atmosphere there should be a scarcity of the finest materials.

It should be remembered, however, that there are great differences in the prevailing wind velocities and that this circumstance will naturally bring together materials ranging through great differences in coarseness. It has lately been shown[1] that such differences are great, even within the limits of a minute of time. As a result there will be a chance for a considerable range in size of particles composing the bulk of any aerial sediment, a range which it is believed might be expressed for the diameters of such particles by the numbers 1 and 100. Of course the range of the extremes will be much greater.

Deposition of dust will take place where wind is caused to slacken its speed.

This is so self-evident that it appears superfluous to mention it. It may be presumed that such a slackening will take place over continental basins, where the general direction of the wind's

[1] S. P. LANGLEY: Internal Work of the Wind.

progress is transverse to the bounding highlands. It may also be presumed that the wind retards its velocity, when going down an inclined plane. The greater depth of the atmospheric ocean in these instances ought to have the same influence on the general current as the widening or deepening of a river channel. If this be the case with extensive continental depressions, valleys of rivers and smaller depressions of the earth's surface ought to produce somewhat similar effects in retarding the passing wind and inducing it to give up a part of the dust it may happen to carry along. On the other hand, when the wind passes over land covered by a growth of timber or only tall grass, its lowest part will be held comparatively still and will drop its load. Did the same air remain among the vegetation all the time this unloading process would stop with the first deposit, but as the eddies no doubt keep up a slow but constant exchange with the air above, the accumulation continues as long as there is any dust left.

Several important deductions can be drawn from the foregoing considerations.

The velocities in the atmosphere being so much greater than those obtaining in rivers, lakes, and seas, the distances over which materials may be transported in it will be correspondingly greater. In the sea sediments are carried out 200 miles and even farther. In the atmosphere, where the velocities often are 100 times greater than those in the sea, dust may, no doubt, be transferred a distance of several hundreds, if not a few thousands of miles. The very finest particles may be borne round the earth, as shown by the dust of Krakatoa, or may, indeed, circle about it for some time.

The greater depth of the aerial ocean renders it but little dependent in its movements on smaller elevations of the land. In a sea five miles deep an elevation of the bottom 8,000 feet high would interpose no serious obstacle to a general forward movement of the whole body of the fluid. Few of our mountain ranges exceed this height, and it would not seem impossible, therefore, that dust in some notable quantities should be carried

across a mountain range, provided there be a favorable current in the upper part of the atmosphere.

While the conditions requisite for much aerial erosion are limited to rather small areas on the land of the globe, there can be little doubt that deposition is much more general and widespread. For dust is carried everywhere. And if it be conceded that the atmosphere is never entirely free from dust, it follows that sedimentation occurs wherever and whenever there is a comparative calm. In places in the ocean, where sedimentation is known to be very slow, atmospheric dust may be supposed to form an appreciable part of the deposits.

The areas of deposition being much greater than the areas of erosion, it is evident the accumulations of atmospheric sediments as a rule are insignificant, only exceptionally exceeding on the land the secular erosion by water, and therefore accumulating only in such exceptional cases.

From a dynamical point of view the wind-theory would appear to furnish an adequate explanation of the occurrence of the loess in the Mississippi valley, at least as to most of its phases. The recent denudation of the western plains, of the bad lands, and of the Cordilleran plateau is extensive enough to furnish the materials many times over. The different rocks in these regions and the changeability of the atmospheric currents would combine to bring together and thoroughly mix a variety of materials, like those of which the loess is composed. The winds would naturally distribute over wide areas the heterogeneous but uniform mixture thus produced. When not taken close to exposures of other materials ninety-nine per cent, by weight, of the loess is composed of particles below the size of .1 mm. and it contains only a small proportion of the finest materials common in clays and residuary earths, just as must be the case in an atmospheric sediment. In the United States, lying in the zone of westerly winds, we find the loess in the continental basin east of the arid regions. It is best developed along the westernmost north-and-south drainage valley, that of the Missouri-Mississippi river. Almost everywhere it is heaviest nearest the

watercourses. In northeastern Iowa its distribution shows such remarkable coincidences with the distribution of the primeval forests, as to only leave the uncertainty whether the loess is the cause of the growing of the forest or the forest the cause of the accumulation of the loess.[1]

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[1] See Pl. XXII and XLIV, Eleventh An. Rep. U. S. Geol. Survey. McGee.